

Measurements of CKM angles β/ϕ_1 and α/ϕ_2 at the **BABAR** and **Belle** experiments

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We report measurements of the CKM angles β/ϕ_1 and α/ϕ_2 done by the **BABAR** and **Belle** experiments. Both experiments have collected large data samples, corresponding to a total of more than 1 billion of $B\bar{B}$ pairs, at the e^+e^- asymmetric-energy colliders PEP-II (SLAC) and KEK-B (KEK), respectively.

1. Introduction

CP violation in the Standard Model (SM) [1] is described by an irreducible complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing 3×3 matrix [2]. The equation $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$, which follows from the unitarity of the CKM matrix V , can be depicted as a triangle – called the Unitarity Triangle (UT) – in the complex plane [3]. The main goal of the B -factories is to verify the SM picture of the origin of the CP violation by measuring the angles (denoted by α , β , and γ ¹) and the sides of the UT in B decays. In this review we report results obtained by the **BABAR** and **Belle** collaborations concerning the measurements of the angles α and β .

2. Detectors and Datasets

Measurements reported in this paper have been obtained by the **BABAR** and **Belle** experiments at the asymmetric-energy e^+e^- B factories PEP-II [4] and KEK-B [5], respectively. At the time of writing the two experiments collected more than 430 fb^{-1} and 750 fb^{-1} , respectively, recorded at the $\Upsilon(4S)$ resonance (center-of-mass energy $\sqrt{s} = 10.58$ GeV), which corresponds to a total of approximately 1.3 billion $B\bar{B}$ events. PEP-II and **BABAR** stopped data taking in April, 2008. The **BABAR** and **Belle** detectors are described elsewhere [6, 7].

3. Measurements of β

Measurements of time-dependent CP asymmetries in B^0 meson decays that proceed via the dominant CKM favored $b \rightarrow c\bar{s}$ tree amplitude, such as $B^0 \rightarrow J/\psi K^0$, have provided a precise measurement of angle β , giving a crucial test of the mechanism of CP

violation in the SM [8]. For such decays the interference between this amplitude and the amplitude from $B^0 - \bar{B}^0$ mixing is dominated by the single phase $\beta = \arg[-(V_{cd}V_{cb}^*)/(V_{td}V_{tb}^*)]$ of the CKM mixing matrix. Other quark transitions involving the charm quark which allow for the measurement of angle β , using time-dependent measurements of B^0 decays, are $b \rightarrow c\bar{c}d$ transitions, like $B^0 \rightarrow J/\psi \pi^0$ and $B^0 \rightarrow D^{*+}D^{*-}$, and $b \rightarrow c\bar{u}d$ transitions, like $B^0 \rightarrow D^{(*)0}h^0$. Either tree and loop (penguin) amplitudes can contribute in these transitions, so they are sensitive to New Physics (NP) due to the large virtual mass scale occurring in the penguin loops.

To measure time-dependent CP asymmetries we reconstruct a B^0 decaying into a CP eigenstate (B_{CP}). From the remaining particles in the event we also reconstruct the decay vertex of the other B meson (B_{tag}) and identify its flavor. The difference $\Delta t \equiv t_{CP} - t_{tag}$ of the proper decay times t_{CP} and t_{tag} of the CP and tag B mesons, respectively, is obtained from the measured distance between the B_{CP} and B_{tag} decay vertices and from the known boost of the e^+e^- system. The distribution of the difference Δt is given by

$$P(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau} \{1 \pm [-\eta_f S_f \sin(\Delta m_d \Delta t) - C_f \cos(\Delta m_d \Delta t)]\} \quad (1)$$

where η_f is the CP eigenvalue of final state f , the upper (lower) sign denotes a decay accompanied by a B^0 (\bar{B}^0) tag, τ is the mean B^0 lifetime, and Δm_d is the mixing frequency. The parameters C_f and S_f for the final state f are the CP -violating parameters

$$S_f = \frac{2\text{Im}(\lambda_f)}{|\lambda_f|^2 + 1}, \quad C_f = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2}, \quad (2)$$

where λ_f is a complex parameter depending on the $B^0 - \bar{B}^0$ mixing as well as on the decay amplitudes for both B^0 and \bar{B}^0 to the CP eigenstate².

When only one diagram contributes to the decay process and no other weak or strong phases appear

¹Also denoted by ϕ_2 , ϕ_1 , and ϕ_3 , respectively. The Greek notation, used by **BABAR** experiment, is used throughout this paper.

²Note that in the **Belle** convention $C_f = -A_f$.

in the process, the SM predicts $C_f = 0$ and $S_f = -\eta_f \sin 2\beta$. A nonzero value of the parameter C_f would indicate direct CP violation. Any significant deviation from the SM prediction could be a sign of NP.

An alternative way to measure the angle β is to use measurements of time-dependent CP asymmetries in decays of B^0 mesons to charmless hadronic final states, such as ϕK^0 , $f_0(980)K^0$, $K^+K^-K^0$, $\eta' K^0$, $\pi^0 K^0$, $K_S^0 K_S^0 K_S^0$, $\rho^0 K_S^0$, and ωK_S^0 . These decays are CKM-suppressed $b \rightarrow q\bar{q}s$ ($q = u, d, s$) processes that are dominated by a single penguin amplitude, with the same weak phase as the $b \rightarrow c\bar{c}s$ transition [9]. In these modes, assuming the penguin dominance of the $b \rightarrow s$ transition and neglecting CKM-suppressed amplitudes, the time-dependent CP -violating parameter S_f is expected to be $-\eta_f \sin 2\beta$. However, CKM-suppressed amplitudes and the color-suppressed tree-level diagram introduce additional weak phases whose contribution may not be negligible [10–13]. As a consequence, only an effective $S = -\eta_f \sin 2\beta_{\text{eff}}$ is determined. The deviation $\Delta S = S - (-\eta_f \sin 2\beta)$ has been estimated in several theoretical approaches [11–16]. The estimates are channel and model dependent. Also for these decays the possible presence of additional diagrams with new heavy particles in the loop and new CP -violating phases may contribute to the decay amplitudes. In this case the measurements of significantly larger ΔS are a sensitive probe for NP [10].

3.1. $b \rightarrow c\bar{c}s$ Decays

Decays underlain by $b \rightarrow c\bar{c}s$ transitions are referred to as “golden modes” due to their relatively large branching fractions $\mathcal{O}(10^{-4} – 10^{-5})$, low experimental background levels and high reconstruction efficiencies. They are dominated by a color-suppressed tree diagram and the theoretical uncertainties are small [17]. Hence the prediction $S_f = -\eta_f \sin 2\beta$ and $C_f = 0$ is a good approximation.

BABAR reconstructed the modes B^0 to $J/\psi K_S^0$, $J/\psi K^{*0}$, $\psi(2S)K_S^0$, $J/\psi K_L^0$, $\eta_c K_S^0$, and $\chi_{c1} K_S^0$, extracting the CP -violating parameters from a simultaneous fit to all modes. The amount of data used corresponds to 383 million $B\bar{B}$ pairs [18]. *Belle* reconstructed the modes $B^0 \rightarrow J/\psi K_S^0$ and $B^0 \rightarrow J/\psi K_L^0$ using 535 million $B\bar{B}$ pairs [19]. Recently *Belle* also reported a measurement of the CP -violating parameters in the $B^0 \rightarrow \psi(2S)K_S^0$ channel, using a sample of 657 million $B\bar{B}$ pairs [20]. The *BABAR* and *Belle* results agree within the measurement uncertainties. All results are shown in Table I. A world average, calculated by the Heavy Flavor Averaging Group (HFAG) [21], gives $\sin 2\beta = 0.680 \pm 0.025$, which reduces the total uncertainty on $\sin 2\beta$ to 3.7%. No evidence of direct CP violation is seen in these modes.

BABAR and *Belle* have also reported measurements

Table I Results for decays involving $b \rightarrow c\bar{c}s$ transitions (“golden modes”). The errors are, in order, statistical and systematic.

B^0 decays	$B\bar{B}$ pairs ($\times 10^6$)	Results
BABAR		
$J/\psi K_S^0$, $J/\psi K^{*0}$, $\psi(2S)K_S^0$, $J/\psi K_L^0$, $\eta_c K_S^0$, $\chi_{c1} K_S^0$	383	$\sin 2\beta = 0.714 \pm 0.032 \pm 0.018$ $C = 0.049 \pm 0.022 \pm 0.017$
Belle		
$J/\psi K_S^0$, $J/\psi K_L^0$	535	$\sin 2\beta = 0.642 \pm 0.031 \pm 0.017$ $C = -0.018 \pm 0.021 \pm 0.014$
$\psi(2S)K_S^0$	657	$\sin 2\beta = 0.718 \pm 0.090 \pm 0.033$ $C = -0.039 \pm 0.069 \pm 0.049$
Average	—	$\sin 2\beta = 0.650 \pm 0.029 \pm 0.018$ $C = -0.019 \pm 0.020 \pm 0.015$

of the β angle using the B^0 decay to $D^{*\pm} D^{*\mp} K_S^0$ [22, 23]. This decay proceeds mainly through the $b \rightarrow c\bar{c}s$ transition. A potential interference effect of the decay proceeding through an intermediate resonance can be measured by dividing the B -decay Dalitz plot into regions with $s^+ \leq s^-$ or $s^+ \geq s^-$, where $s^\pm \equiv m^2(D^{*\pm} K_S^0)$. Such an analysis offers the interesting possibility to extract the sign of $\cos 2\beta$, therefore partially resolving the 4-fold ambiguity in the value of β obtained from the measurement of the $\sin 2\beta$. For these modes the time-dependent CP asymmetry is described in terms of the coefficients J_c , J_0 , J_{s1} , and J_{s2} , which are the integrals over the half-Dalitz space. The results are shown in Table II and there is a general agreement between the two experiments. *BABAR* infers that $\cos 2\beta > 0$ at 94% confidence level (CL), on the assumption that $J_{s2} > 0$ [22].

Table II Results for B^0 decay to $D^{*\pm} D^{*\mp} K_S^0$. The errors are, in order, statistical and systematic.

	$B\bar{B}$ pairs ($\times 10^6$)	Results
<i>BABAR</i>	230	$J_c/J_0 = 0.76 \pm 0.18 \pm 0.07$
		$2J_{s1}/J_0 \sin 2\beta = 0.10 \pm 0.24 \pm 0.06$
<i>Belle</i>	449	$2J_{s2}/J_0 \cos 2\beta = 0.38 \pm 0.24 \pm 0.05$
		$J_c/J_0 = 0.60^{+0.25}_{-0.28} \pm 0.08$
		$2J_{s1}/J_0 \sin 2\beta = -0.17 \pm 0.42 \pm 0.09$
		$2J_{s2}/J_0 \cos 2\beta = -0.23^{+0.43}_{-0.41} \pm 0.13$

3.2. $b \rightarrow c\bar{c}d$ Decays

The $B^0 \rightarrow J/\psi\pi^0$ decay takes place through a $b \rightarrow c\bar{c}d$ transition. The dominant tree diagram is Cabibbo suppressed. However there is a penguin diagram of the same order as the tree diagram but with a different weak phase. So, contrary to the golden modes, even within the SM, the deviation of S measured in $b \rightarrow c\bar{c}d$ modes from $-\eta_f \sin 2\beta$ could be substantial. Both *BABAR* and *Belle* have updated measurements for this mode, which are shown in Table III [24, 25]. In particular the *BABAR* result provides evidence of CP violation, with a statistical significance of 4σ , while for *Belle* it is 2.4σ .

The decay $B^0 \rightarrow D^{*+}D^{*-}$ also goes through the $b \rightarrow c\bar{c}d$ transition. This mode requires an angular analysis to disentangle CP -odd and CP -even events. Results for CP -violating parameters are show in Table III [26].

The quark transition $b \rightarrow c\bar{c}d$ is also responsible for the B^0 decays to $D^{*+}D^-$, $D^{*-}D^+$, and D^+D^- . Results for the *BABAR* and *Belle* experiments are shown in Table III [27, 28]. *Belle* reports a statistical significance of 3.2σ for direct CP violation in the D^+D^- mode, while *BABAR* reports 0.4σ .

Within the experimental uncertainties, all results for $b \rightarrow c\bar{c}d$ decays are compatible with the SM prediction.

3.3. $b \rightarrow c\bar{u}d$ Decays

The decay $B^0 \rightarrow D_{CP}^{(*)0} h^0 (h^0 = \pi^0, \eta, \omega)$ is governed by a color-suppressed $b \rightarrow c\bar{u}d$ tree diagram. When the neutral D meson decays to a CP eigenstate Eq. 1 is still valid. In these modes the possible effects of NP are expected to be small, so we expect $S = \sin 2\beta$ [9]. Only *BABAR* reported a measurement of such decays [29], by reconstructing the following decay modes $D^{*0} \rightarrow D^0\pi^0$ and $D^0 \rightarrow K^+K^-$, $D^0 \rightarrow K_S^0\pi^0$ and $D^0 \rightarrow K_S^0\omega$. The analysis is performed using $383 \times 10^6 B\bar{B}$ pairs from which 340 ± 32 signal events are reconstructed. The measured CP -violating parameters,

$$\begin{aligned} \sin 2\beta &= 0.56 \pm 0.23(\text{stat}) \pm 0.05(\text{syst}) \\ C &= -0.23 \pm 0.16(\text{stat}) \pm 0.04(\text{syst}), \end{aligned}$$

are consistent with the SM expectations.

Also the decay $B^0 \rightarrow D^{(*)0}h^0$, where $h^0 = \pi^0, \eta, \omega, \eta'$, is governed by the $b \rightarrow c\bar{u}d$ tree diagram. This decay can occur with and without $B^0 - \bar{B}^0$ mixing and interference effects being visible across the $D^0 \rightarrow K_S^0\pi^+\pi^-$ Dalitz plot. The interesting result from this measurement is the possibility to extract the sign of $\cos 2\beta$ in order to resolve the 4-fold ambiguity in the value of β obtained from the measurement of the $\sin 2\beta$. The results from *BABAR* are obtained using

Table III Results for B^0 decays to $J/\psi\pi^0$, $D^{*+}D^{*-}$, $D^{*+}D^-$, $D^{*-}D^+$, and D^+D^- ($b \rightarrow c\bar{c}d$ decays). The errors are, in order, statistical and systematic.

		$B\bar{B}$ pairs ($\times 10^6$)	Results
$J/\psi\pi^0$			
<i>BABAR</i>	466	$S = -1.23 \pm 0.21 \pm 0.04$ $C = -0.20 \pm 0.19 \pm 0.03$	
<i>Belle</i>	535	$S = -0.65 \pm 0.21 \pm 0.05$ $C = -0.08 \pm 0.16 \pm 0.05$	
$D^{*+}D^{*-}$			
<i>BABAR</i>	383	$S = -0.66 \pm 0.19 \pm 0.04$ $C = -0.02 \pm 0.11 \pm 0.02$	
<i>Belle</i>	657	$S = -0.93 \pm 0.24 \pm 0.15$ $C = -0.16 \pm 0.13 \pm 0.02$	
$D^{*+}D^-$			
<i>BABAR</i>	383	$S = -0.79 \pm 0.21 \pm 0.06$ $C = 0.18 \pm 0.15 \pm 0.04$	
<i>Belle</i>	152	$S = -0.55 \pm 0.39 \pm 0.12$ $C = -0.37 \pm 0.22 \pm 0.06$	
$D^{*-}D^+$			
<i>BABAR</i>	383	$S = -0.44 \pm 0.22 \pm 0.06$ $C = 0.23 \pm 0.15 \pm 0.04$	
<i>Belle</i>	152	$S = -0.96 \pm 0.43 \pm 0.12$ $C = 0.23 \pm 0.25 \pm 0.06$	
D^+D^-			
<i>BABAR</i>	383	$S = -0.54 \pm 0.34 \pm 0.06$ $C = 0.11 \pm 0.22 \pm 0.07$	
<i>Belle</i>	535	$S = -1.13 \pm 0.37 \pm 0.09$ $C = -0.91 \pm 0.23 \pm 0.06$	

383 million of $B\bar{B}$ pairs:

$$\begin{aligned} \sin 2\beta &= 0.29 \pm 0.34(\text{stat}) \pm 0.03(\text{syst}) \pm 0.05(\text{Dalitz}) \\ \cos 2\beta &= 0.42 \pm 0.49(\text{stat}) \pm 0.09(\text{syst}) \pm 0.13(\text{Dalitz}), \end{aligned}$$

leading to a preferred positive sign for $\cos 2\beta$ at 86% CL [30]. The Dalitz error refers to the Dalitz model parameterization used in the analysis. *Belle* performed a similar analysis using 386 million of $B\bar{B}$ pairs:

$$\begin{aligned} \sin 2\beta &= 0.78 \pm 0.44(\text{stat}) \pm 0.22(\text{syst + Dalitz}) \\ \cos 2\beta &= 1.87^{+0.40}_{-0.53}(\text{stat})^{+0.22}_{-0.32}(\text{syst + Dalitz}), \end{aligned}$$

which gives a preferred positive sign of $\cos 2\beta$ at 98.3% CL [31].

3.4. $b \rightarrow s$ Decays

No major updates on the $b \rightarrow s$ decays have been reported by the *BABAR* and *Belle* recently. The sum-

mary of results for the time-dependent S parameter is shown in Fig. 1 [21]. In general the results are consistent between *BABAR* and *Belle*, and consistent with SM expectations within the statistical uncertainties. Some tensions are observed for the $B^0 \rightarrow \pi^0\pi^0K_s^0$ decay results with respect to the SM expectation. Also tensions are observed in $B^0 \rightarrow f_0(980)K_s^0$ decay between *BABAR* and *Belle* results. However, in this case the *BABAR* result reported in the figure is a combination of results from the two Dalitz plot analyses, considering $f_0(980) \rightarrow K^+K^-$ and $f_0(980) \rightarrow \pi^+\pi^-$, while *Belle* uses only the $f_0(980) \rightarrow \pi^+\pi^-$ mode. The results are found to be in agreement if only the $f_0(980) \rightarrow \pi^+\pi^-$ decay is considered. No evidence of direct CP violation is observed.

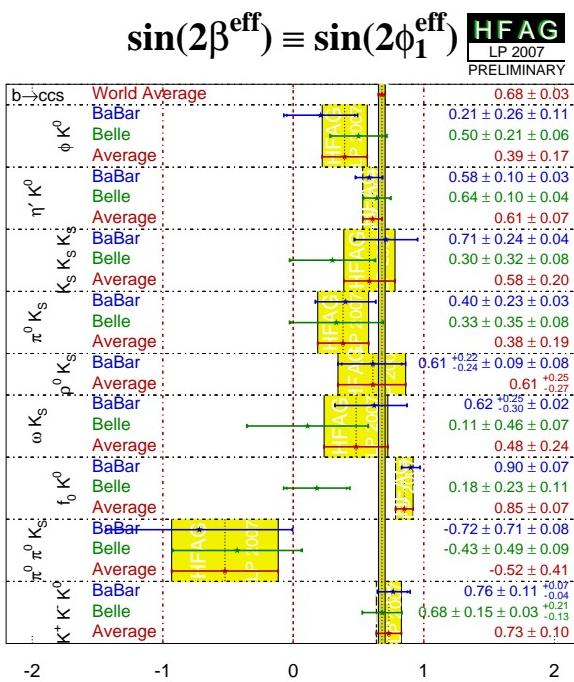


Figure 1: Summary of time-dependent S parameter results for $b \rightarrow s$ penguin modes [21].

4. Measurements of α

The UT angle α , defined as $\arg[-(V_{td}V_{tb}^*)/(V_{ud}V_{ub}^*)]$, can be determined by measuring a time-dependent CP asymmetry in charmless $b \rightarrow u\bar{u}d$ decays such as $B^0 \rightarrow \pi^+\pi^-$, $\pi^+\pi^-\pi^0$, $\rho^+\rho^-$, and $a_1^\pm(1260)\pi^\mp$, in a way similar to what described in section 3. The B decays proceed mainly through a tree and gluonic penguin amplitude.

4.1. $B^0 \rightarrow \pi^+\pi^-$ and $B^0 \rightarrow \rho^+\rho^-$ Decays

Similar to Eq. 1, the time-dependent rate for $B^0 \rightarrow \pi^+\pi^-$ is given by

$$P(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau} \{1 \pm [S \sin(\Delta m_d \Delta t) - C \cos(\Delta m_d \Delta t)]\} \quad (3)$$

where C and S are CP asymmetry coefficients. If the decay amplitude is dominated by a tree diagram then $S = \sin 2\alpha$ and $C = 0$. The presence of an amplitude with a different weak phase (such as from a gluonic penguin diagram) gives rise to direct CP violation and shifts S from $\sin 2\alpha$ to

$$S = \sqrt{1 - C^2} \sin 2\alpha_{\text{eff}}, \quad (4)$$

where $\alpha_{\text{eff}} = \alpha + \delta\alpha$, and $\delta\alpha$ is the phase shift.

The *BABAR* and *Belle* results for $B^0 \rightarrow \pi^+\pi^-$ time-dependent CP -violating parameters are shown in Table IV [35, 36]. Both measurements indicate a large mixing-induced CP -violation with a significance greater than 5σ independent of the value of C . *Belle* has also observed large direct CP violation (5.5σ). The difference between *BABAR* and *Belle* on the (S, C) plane is about 2.1σ [21]. The angle α can be extracted using isospin relations, which require the measurement of the branching fractions and CP -violating parameters for the SU(2) partners of the $B^0 \rightarrow \pi^+\pi^-$ decay: $B^0 \rightarrow \pi^0\pi^0$ and $B^\pm \rightarrow \pi^0\pi^\pm$ [32]. The *BABAR* and *Belle* constraints on α are consistent with the SM and are given by $(96^{+10}_{-6})^\circ$ and $(97 \pm 11)^\circ$, respectively, at 68% CL.

Another decay used to measure the angle α is $B^0 \rightarrow \rho^+\rho^-$. For this mode the same considerations described above for the $B^0 \rightarrow \pi^+\pi^-$ mode are still valid. The *BABAR* and *Belle* results are shown in Table IV [38, 39]. Both experiments are consistent with each other and consistent with no CP violation. To extract α using SU(2) relations, *BABAR* has recently performed the measurement of the time-dependent CP -violating parameters in $B^0 \rightarrow \rho^0\rho^0$ with 427 million of $B\bar{B}$ pairs, measuring a branching fraction of $(0.84 \pm 0.29 \pm 0.17) \times 10^{-6}$, a longitudinal polarization of $0.70 \pm 0.14 \pm 0.05$ and for the longitudinally polarized events $S_L = 0.5 \pm 0.9 \pm 0.2$ and $C_L = 0.4 \pm 0.9 \pm 0.2$ (errors are statistical and systematic, respectively) [40]. Together with all other measurements from SU(2) partners, it results $74^\circ < \alpha < 117^\circ$ at 68% CL, with a constraint of $|\delta\alpha| < 14.5^\circ$ at 68% CL and a preferred solution of $\delta\alpha = +11.3^\circ$. *Belle*, using data of 657 million of $B\bar{B}$ pairs, set an upper limit on the branching fraction for $B^0 \rightarrow \rho^0\rho^0$ of 1.0×10^{-6} at 90% CL, and have yet to measure the time-dependent CP -violating parameters for this mode. The *Belle* constraint on α is $(91.7 \pm 14.9)^\circ$ [41].

Table IV Results for B^0 decays to $\pi^+\pi^-$ and $\rho^+\rho^-$. Note that the CP -violating parameters for $B^0 \rightarrow \rho^+\rho^-$ refer to longitudinally polarized events. The errors are, in order, statistical and systematic.

	$B\bar{B}$ pairs ($\times 10^6$)	Results
$\pi^+\pi^-$		
BABAR	383	$S = -0.60 \pm 0.11 \pm 0.03$
		$C = -0.21 \pm 0.09 \pm 0.02$
Belle	535	$S = -0.61 \pm 0.10 \pm 0.04$
		$C = -0.55 \pm 0.08 \pm 0.05$
$\rho^+\rho^-$		
BABAR	383	$S_L = -0.17 \pm 0.20^{+0.05}_{-0.06}$
		$C_L = 0.01 \pm 0.15 \pm 0.06$
Belle	535	$S_L = 0.19 \pm 0.30 \pm 0.08$
		$C_L = -0.16 \pm 0.21 \pm 0.08$

4.2. $B^0 \rightarrow \pi^+\pi^-\pi^0$ ($\rho\pi)^0$ and $B^0 \rightarrow a_1^\pm(1260)\pi^\mp$ Decays

An alternative way to measure the angle α is to perform a time-dependent Dalitz plot analysis in $B^0 \rightarrow \pi^+\pi^-\pi^0$ decays. We model the interference between the intersecting ρ resonance bands and so determines the strong phase differences from the Dalitz plot structure [42]. The Dalitz amplitudes and time-dependence are contained in complex parameters that are determined by fit on data. This technique allows to extract directly α . *BABAR* and *Belle* have performed measurements using 383 million and 449 million of $B\bar{B}$ pairs, respectively. The intervals at 68% CL are $74^\circ < \alpha < 132^\circ$ for *BABAR* [43] and $68^\circ < \alpha < 95^\circ$ for *Belle* [44].

Another channel which allows for a measurement of α is $B^0 \rightarrow a_1^\pm(1260)\pi^\mp$. For this mode a Dalitz plot analysis is not feasible with current statistics, so a quasi-two-body approach is used. As the final state $a_1^\pm(1260)\pi^\mp$ is not a CP eigenstate, one has to consider four decay modes, divided in two groups, with different charge and flavor combinations: $B^0 \rightarrow a_1^+(1260)\pi^-$ and $\bar{B}^0 \rightarrow a_1^+(1260)\pi^-$; $B^0 \rightarrow a_1^-(1260)\pi^+$ and $\bar{B}^0 \rightarrow a_1^-(1260)\pi^+$. Equation 3 is valid for each group, where we denote the CP -violating parameters as S^+, C^+ and S^-, C^- , respectively [45]. It is possible to redefine these parameters as $S = (S^+ + S^-)/2$, $C = (C^+ + C^-)/2$, $\Delta S = (S^+ - S^-)/2$, $\Delta C = (C^+ - C^-)/2$. *BABAR* performed this analysis using 383 million of $B\bar{B}$ pairs [46], extracting 608 ± 52 signal events and the following time-dependent CP -violating parameters:

$$\begin{aligned} S &= 0.37 \pm 0.21 \pm 0.07 \\ C &= -0.10 \pm 0.15 \pm 0.09 \end{aligned}$$

$$\begin{aligned} \Delta S &= -0.14 \pm 0.21 \pm 0.06 \\ \Delta C &= 0.26 \pm 0.15 \pm 0.07 \end{aligned}$$

where the errors are, in order, statistical and systematic. Also a time- and flavour-integrated charge asymmetry for direct CP violation has been measured, $A_{CP} = -0.07 \pm 0.07 \pm 0.02$. These measurements indicate no direct and time-dependent CP violation in $B^0 \rightarrow a_1^\pm(1260)\pi^\mp$ decay. The effective angle α_{eff} is $(78.6 \pm 7.3)^\circ$. The extraction of α can be performed by evoking SU(3) flavor symmetry [45]. Once the measurements of the branching fractions for the SU(3)-related decays become available, it will be possible to determine an upper bound on $\delta\alpha$ in $B^0 \rightarrow a_1^\pm(1260)\pi^\mp$ decays and therefore yield a constraint on the angle α .

5. Conclusions

In this review we have presented measurements done by the *BABAR* and *Belle* experiments that are used to determine the angles β and α of the UT. The world averages values are $\beta = (21.5 \pm 1.0)^\circ$ [21] and $\alpha = (87.5^{+6.2}_{-5.3})^\circ$ [47]. The CP -violating parameters are consistent with the Standard Model expectations within the uncertainties of the measurements.

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References

- [1] S. Weinberg, Phys. Rev. Lett. **19**, 1264 (1967); A. Salam, “Elementary Particle Physics”, edited by N. Svartholm (Almqvist and Wiksell, Stockholm 1968), p. 367; S. Weinberg, Phys. Rev. Lett. **37**, 657 (1976).
- [2] N. Cabibbo, Phys. Rev. Lett. **10**, 531 (1963); M. Kobayashi, M. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).
- [3] C. Amsler *et al.* Phys. Lett. B **667**, 1 (2008).
- [4] PEP-II Conceptual Design Report, SLAC-PUB-0418 (1993).
- [5] S. Kurokawa and E. Kikutani, Nucl. Instr. Meth. A **499**, 1 (2003).
- [6] *BABAR* Collaboration, B. Aubert *et al.*, Nucl. Instr. Meth. A **479**, 1 (2002).
- [7] *Belle* Collaboration, A. Abashian *et al.*, Nucl. Instr. Meth. A **479**, 117 (2002).

- [8] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **89**, 201802 (2002); *Belle* Collaboration, K. Abe *et al.*, Phys. Rev. D **66**, 071102 (2002).
- [9] Y. Grossman and M. P. Worah, Phys. Lett. B **395**, 241 (1997); D. Atwood and A. Soni, Phys. Lett. B **405**, 150 (1997); M. Ciuchini *et al.*, Phys. Rev. Lett. **79**, 978 (1997).
- [10] D. London and A. Soni, Phys. Lett. B **407**, 61 (1997).
- [11] Y. Grossman *et al.*, Phys. Rev. D **68**, 015004 (2003).
- [12] C.-W. Chiang *et al.*, Phys. Rev. D **68**, 074012 (2003); M. Gronau *et al.*, Phys. Lett. B **596**, 107 (2004).
- [13] M. Beneke and M. Neubert, Nucl. Phys. B **675**, 333 (2003).
- [14] M. Beneke, Phys. Lett. B **620**, 143 (2005); G. Buchalla *et al.*, JHEP **0509**, 074 (2005).
- [15] H. Y. Cheng *et al.*, Phys. Rev. D **72**, 014006 (2005), Phys. Rev. D **71**, 014030 (2005); S. Fajfer *et al.*, Phys. Rev. D **72**, 114001 (2005).
- [16] A. R. Williamson and J. Zupan, Phys. Rev. D **74**, 014003 (2006).
- [17] M. Ciuchini *et al.*, Phys. Rev. Lett. **95**, 221804 (2005).
- [18] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **99**, 171803 (2007).
- [19] *Belle* Collaboration, K.-F. Chen *et al.*, Phys. Rev. Lett. **98**, 031802 (2007).
- [20] *Belle* Collaboration, H. Sahoo *et al.*, Phys. Rev. D **77**, 091103 (2008).
- [21] Heavy Flavor Averaging Group, <http://www.slac.stanford.edu/xorg/hfag/triangle/>, Winter 2008 update.
- [22] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. D **74**, 091101 (2006).
- [23] *Belle* Collaboration, J. Dalseno *et al.*, Phys. Rev. D **76**, 072004 (2007).
- [24] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **101**, 021801 (2008).
- [25] *Belle* Collaboration, S. E. Leo *et al.*, Phys. Rev. D **77**, 071101 (2008).
- [26] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. D **76**, 111102 (2007).
- [27] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **99**, 071801 (2007).
- [28] *Belle* Collaboration, T. Aushev *et al.*, Phys. Rev. Lett. **93**, 201802 (2004); *Belle* Collaboration, S. Fratina *et al.*, Phys. Rev. Lett. **98**, 221802 (2007);
- [29] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **99**, 081801 (2007).
- [30] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **99**, 231802 (2007).
- [31] *Belle* Collaboration, P. Krokovny *et al.*, Phys. Rev. Lett. **97**, 081801 (2006).
- [32] M. Gronau and D. London, Phys. Rev. Lett. **65**, 3381 (1990); H. J. Lipkin *et al.*, Phys. Rev. D **44**, 1454 (1991); M. Gronau, Phys. Lett. B **265**, 389 (1991).
- [33] Y. Grossman and H. R. Quinn, Phys. Rev. D **58**, 017504 (1998); J. Charles, Phys. Rev. D **59**, 054007 (1999); M. Gronau *et al.*, Phys. Lett. B **514**, 315 (2001).
- [34] M. Gronau and J. Zupan, Phys. Rev. D **70**, 074031 (2004).
- [35] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **99**, 021603 (2007); *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. D **76**, 091102 (2007).
- [36] *Belle* Collaboration, H. Ishino *et al.*, Phys. Rev. Lett. **98**, 211801 (2007).
- [37] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **98**, 111801 (2007).
- [38] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. D **76**, 052007 (2007).
- [39] *Belle* Collaboration, A. Somov *et al.*, Phys. Rev. D **76**, 011104 (2007).
- [40] *BABAR* Collaboration, B. Aubert *et al.*, arXiv:0708.1630.
- [41] *Belle* Collaboration, C.-C. Chiang *et al.*, arXiv:0808.2576.
- [42] A. E. Snyder and H. R. Quinn, Phys. Rev. D **48**, 2139 (1993).
- [43] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. D **76**, 012004 (2007).
- [44] *Belle* Collaboration, A. Kusaka *et al.*, Phys. Rev. Lett. **98**, 221602 (2007). *Belle* Collaboration, A. Kusaka *et al.*, Phys. Rev. D **77**, 072001 (2008).
- [45] M. Gronau and J. Zupan, Phys. Rev. D **73**, 057502 (2006).
- [46] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **98**, 181803 (2007).
- [47] CKMfitter Group, J. Charles *et al.*, Eur. Phys. J. C **41**, 1 (2005).